# Pigtailing the high-Q microsphere cavity: A simple fiber coupler for optical whispering-gallery modes

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*Introduction:* Optical microsphere cavities [1], with their exceptionally high quality-factor (up to $Q{\sim}10^{10}$ demonstrated to date [2]) and submillimeter dimensions, present an attractive new building block for fiber optics and photonics applications. Besides the straightforward use as ultra-compact narrow-band filters and spectrum analyzers, the proposed applications included microlaser [3], optical locking for laser linewidth narrowing [4], and replacement of fiber delays in optoelectronic microwave oscillator [5]. Strain, temperature and ambient medium sensitivity of whispering-gallery (WG) mode frequencies and Q can be the basis for variety of ultra-compact modulators and sensors.

Prospects for microsphere applications have suffered from the lack of simple and compact coupler devices compatible with modern fiber-optic hardware. The light is strongly confined in WG modes: radiative Qs more than $10^{20}$ are typical for hundred-micron size silica spheres. Therefore, if no modification - such as grating - is made on the sphere proper, light has to be launched by means of overlapping the evanescent field of the modes with that of a phase-matched waveguide or optimized total internal reflection spot in adjacent coupling prism [6]. Although proved to be most flexible and versatile, the prism coupler is bulky and requires collimation and focusing optics to work with optical fiber. The previously reported attempts to directly couple a microsphere to an optical fiber had limited efficiency due to remaining phase mismatch (side-polished bent fiber coupler [7]), or still considerable size including long core-to-cladding transformers (tapered monomode fiber coupler [8]). In this paper, we report a new and simple method of direct fiber coupling to high-Q WG modes in microsphere, which in essense is a hybrid of waveguide and prism coupler.

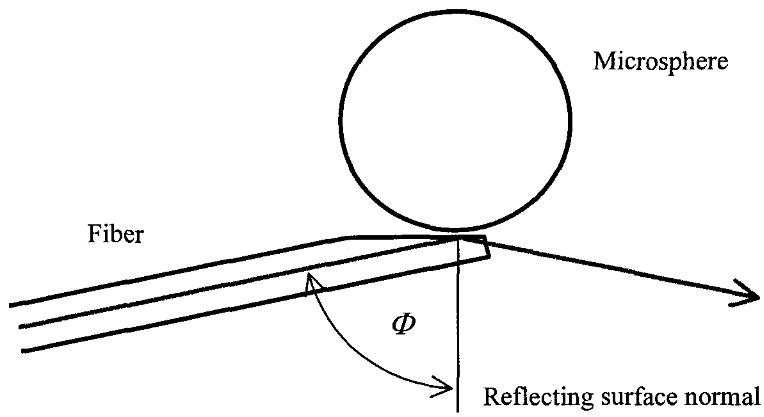


Fig.1. Schematic of the angle-polished fiber coupler for high-Q whispering-gallery modes in microsphere

*Angle-polished fiber tip as phase-matched coupler for whispering-gallery modes:* The idea of the new coupler is illustrated in Fig.1. The tip of a cleaved single-mode fiber is angle-polished under steep angle. Upon incidence on the angled surface, the light propagating inside the fiber core undergoes total internal reflection and escapes the fiber. With the sphere positioned in the range of the evanescent field from the core area, the configuration provides efficient energy exchange in resonance between the waveguide mode of single-mode fiber and the whispering-gallery mode in the sphere. The angle of the polish is chosen to secure the phase matching requirement: $\Phi = arcsin(n_{sphere}/n_{fiber})$. Here $n_{fiber}$ stands for the effective refraction index to describe the guided wave in the fiber core truncation area, and $n_{sphere}$ stands for the effective refraction index to describe azimuthal propagation of WG modes (considered as closed waves undergoing total internal reflection in the sphere). Since the linear dimensions of the angle-cut core area match well the area of evanescent field overlap, the new system is equivalent to a prism coupler with eliminated collimation/focusing optics.

*Phase matching condition:* The effective refraction index to describe the azimuthal propagation of WG modes near the surface of the sphere can be calculated, for example, on the basis of asympthotic expressions [9] for WG mode frequencies $\omega_{lq}$ , where $n_{sphere} = cl / a\omega_{lq}$ . Here $l$, $q$ are azimuthal and radial mode indexes respectively; $a$ – sphere radius; $c$ – speed of light. Presented in Fig.2 are results of calculation of $n_{sphere}$ (at the wavelength 1310nm) for fused silica spheres of different radius. The calculation is made for three lowest radial order modes $TE\ (TM)_{lmq}$, $q$=1,2,3.

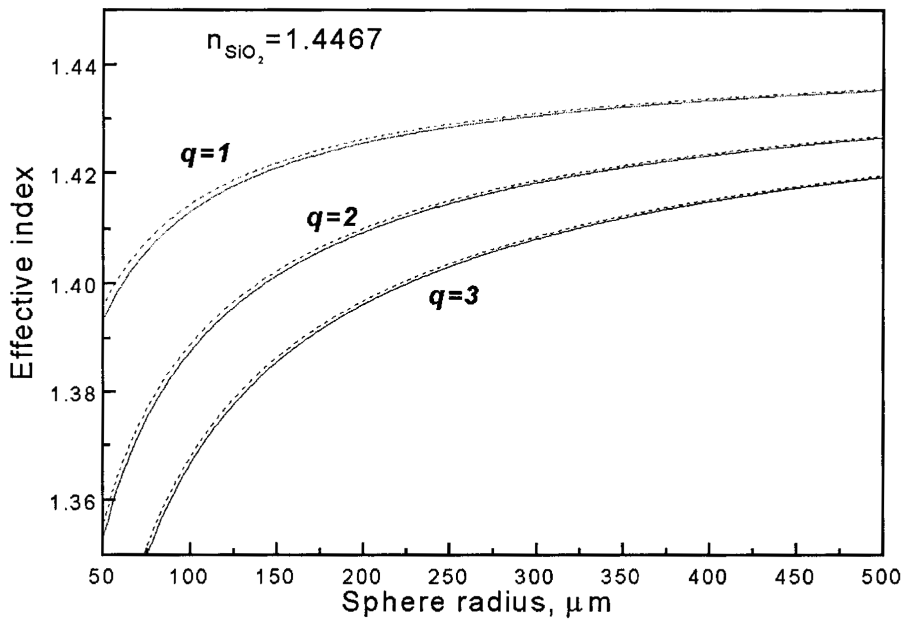


Fig.2. Effective refraction index for azimuthal propagation of $TE_{lmq}$ (solid) and $TM_{lmq}$ (dashed) modes in silica spheres at 1310nm (based on WG mode frequency approximation by C.C.Lam *et al* [9])

Since the guided wave in the fiber no longer exists after reflection from truncation plane, precise calculation of $n_{fiber}$ is a non-trivial task. However, as an initial approximation, one can assume it to be equal to the effective index $n_{guide}$ of the guided wave in the regular fiber. In our experiment we used standard Corning SMF-28 fiber with the germanium-doped core, silica cladding and core-to-cladding index difference 0.36%. To specify experimentally the effective index of the fiber at our wavelength 1310nm, we built a $F \sim 10$ finesse ring interferometer with a 2x2 fused coupler of 10% coupling ratio. The coupler was made of the same SMF-28 fiber under study. The ring interferometer was connected to a probe DFB laser (1310nm) at the input and a photodetector at the output. The fringes were observed as dips in the transmitted power upon sweeping the laser frequency. The probe signal was modulated by a $LiNbO_3$ phase modulator at the frequency about half the value of the free spectral range (FSR). Precise value of the FSR was obtained by matching the sidebands from the neighbouring fringes. The measured free spectral range $(280.1 \pm 0.3)$MHz, with the total loop length of $(73.21 \pm 0.05)$cm yielded the value $n_{guide} = 1.4625 \pm 0.0019$.

As follows from Fig.2, for the lowest order $TE\ (TM)_{lml}$ modes, the effective index varies from 1.394 to 1.435 in the spheres of radius 50 to 500 μm, and the corresponding optimal truncation angle of SMF-28 fiber $\Phi$ (based on the guided mode effective index) lays within the range between 72° and 79°. For the microsphere used in our experiment below (radius 235μm), the optimal angle was 77.6°.

*Experiment:* We have prepared two fiber couplers of the new type by angle-polishing the cleaved SMF-28 fiber tips. Complete crossing of the core area was detected *in situ* by sending the visible radiation into the fiber and monitoring the output emission of the tip. The polishing angles of the two fibers were about 12.1° and 13.3° ( $\Phi = 77.9°$ and $76.7°$ correspondingly).

Fig.3 presents a close-up view of assembly consisting of two fiber couplers and a silica microsphere (of the radius 235μm). Dark area in the bottom is the out-of-focus image of the conical fused silica rod supporting the microsphere.

Fig.3. The close-up of a silica microsphere (radius 235μm) and two angle-polished fiber couplers

Since the remaining cleave surface provides only slight refraction of the output emission of the reflected emission of the core, the alignment can be done by the observation of the interference of exciting beam and mode re-emission to the coupler in the far field. Efficiency of the input and output coupling in the system presented in Fig.3 was checked by the simultaneous monitoring the overall intensity of the free beam escaping the input fiber tip, and the power trasmitted to the output coupler, as functions of frequency tuning of the probe 1.3μm DFB laser. Results are presented in Fig.4; the gaps between the sphere and two couplers were optimized to obtain maximum contrast of resonances in the input coupler signal; and maximum power in the outcoupler. The unloaded quality-factor of the sphere was $Q_o = 1.1\times10^8$.

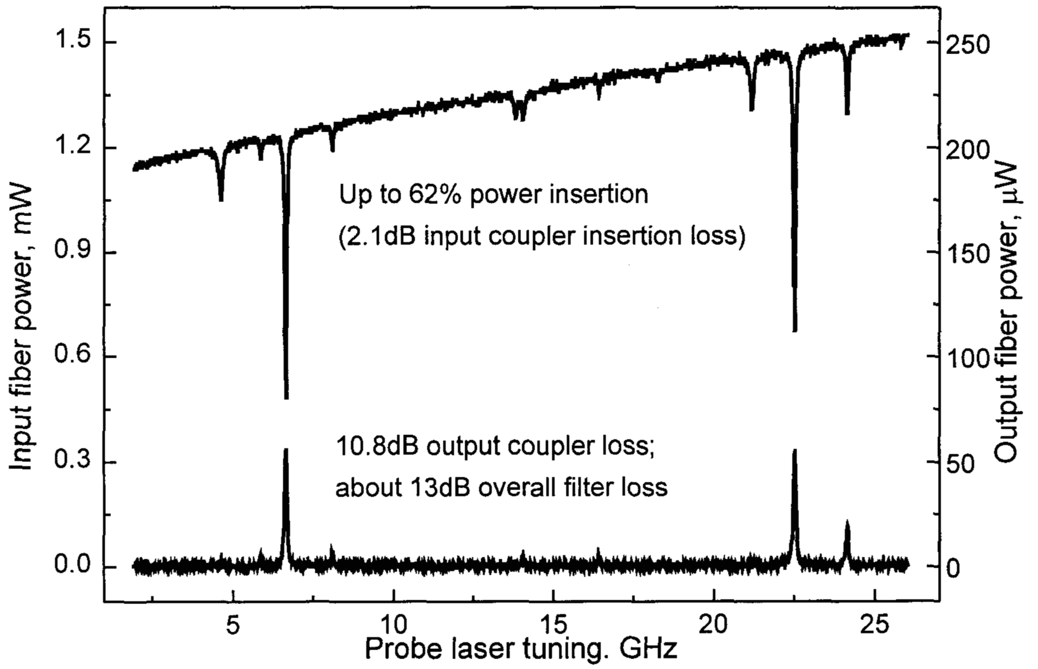


Fig.4. Characterization of the coupling efficiency of angle-polished fiber coupler assembly with fused silica microsphere. The slope of the upper curve is due to variation of the probe 1.3μm DFB laser power upon tuning

As seen in Fig.4, efficiency of the new angle-polished fiber coupler (over 60% power insertion in the mode) is comparable to the best previously reported coupler devices (prism and fiber taper). Relativly poor (about 10%) outcoupling efficiency in our first experiment was due to insufficient flexibility of the translation stage that provided the coplanar alignment of the two couplers with respect to the symmetry plane of residual non-sphericity of the cavity. It is evident, however, that with improved alignment, efficiency of the coupling can be symmetrized, resulting in overall ~4dB insertion loss in the system considered as narrow-band transmission filter.

Further optimization of the coupling (to approach 0dB losses – critical coupling - at resonance) may require additional optimization of the index and/or cross section of the fiber core. This is due to the fact that the optimal coupling conditions imply not only phase matching but also maximization of the coupler and sphere mode field overlap in the interaction area.

*Conclusion*: We have demonstrated a simple and efficient direct coupling method for very high-Q whispering-gallery modes in optical microsphere cavities with standard single-mode optical fiber. Simple "pigtailing" of microspheres facilitates their wider use in photonics, in a whole class of new devices ranging from ultra-compact narrow band filters and spectrum analyzers through high-sensitivity modulators and sensors, to compact laser frequency stabilization schemes and opto-electronic microwave oscillators.

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